Effects of Additional Coldwork Stress on Temperature Compensation Material

Bruce C. Brown
Magnet Test Facility
Fermi National Accelerator Laboratory *
P.O. Box 500
Batavia, Illinois 60510

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Abstract

For temperature compensation of the field strength of Strontium
Ferrite permanent magnets, we are investigating the use of Ni-Fe alloys.
We have investigated the effects of the additional stresses introduced
to the materials on the B-H curve. We conclude that the the stress
changes required for the planned fabrication steps create small effects
on the B-H at room temperature.

1   Introduction

Investigations which are underway to build hybrid permanent magnets
for a storage ring at Fermilab have focused on designs in which temperature
stability is achieved by a temperature compensating flux shunt using Ni-Fe
compensating materials[1]. We expect to use materials obtained as 1" x
.050" rolls which will be cut to length (typically 6" sections) and installed.
Since stress is introduced in the manufacturing process and additional stress
will be introduced as we fabricate parts and assemble magnets, we have
investigated the effects of additional stress levels on the B-H curve of one
lot of this material. In magnet designs under current consideration, the
compensator material will experience an H field of about 1000 - 2000 Oe.

Although details of the manufacturing process are proprietary, the ven-
dors have indicated that the rolling and annealing processes are critical to
achieving linear response with temperature. We have decided to investigate
whether the fabrication steps we envision are likely to introduce important
modifications in the compensation response of the materials.

2   Hypothesis and Test Plan

The test design assumes that the manufacturing process produces rolls
of material of the desired width and with the specified properties. Lengths
of compensator will be cut from these rolls to produce parts for assembly.
This will be done either by the compensator vendor or as a subsequent
fabrication step. As a minimum, this will involve some flattening of the
material, a process which introduces additional stress into the compensator.
We seek to confirm a null hypothesis (no measurable effect) by introducing a
stress change many times larger than the required fabrication tests. If only
small effects are observed, we assume that great care will not be required in
the fabrication process.

In the applications we are considering, the compensation is determined by the value of dB_r/dT where B_r is the intercept of a tangent to the B-H curve at the operating point. The reduction in magnet strength due to the compensator is determined by the value of B_r. As will be shown here, the B-H curve is quite linear in the region of interest. This test will measure the B-H curve at room temperature. Temperature dependent studies are assumed unnecessary if the measured effect is small.

As a substitute for a more detailed understanding of the entire process, we monitored changes in the mechanical hardness of the sample. This was measured as received, after coldwork, and after annealing.

3   Tests

3.1   Sample Preparation

Fermilab has received a shipment of Temperature Compensator 30 Type 4 (TC 30 Type 4) from Carpenter Technologies (CarTech) for Magnet R&D[1]. Coils had an inside radius of 16".

For high field tests, the material was cut into 6" long strips (observed radius about 40") and processed:

- Roll to increase initial curvature to radius between 3" and 4".

- Roll to straighten.

- Roll to reverse initial curvature to radius between 3" and 4".

- Roll to straighten (final).

- Perform B-H measurements.

For tests using the Epstein Frame and the LDJ Hysteresigraph[2], the material was cut into 12" long strips (observed radius about 40") and processed:

- Perform Epstein Test.

- Perform Hardness Test.

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[1] Purchase Order S48730, 4/10/95 is for 1000 lbs. of alloy which has been received in coils of 1" wide by 0.050" thick material.

[2] LDJ Model 5500 Hysteresigraph, LDJ Electronics, Inc. Stephenson Hwy. P.O. Box 219, Troy, MI 48009-0219

- Roll to increase initial curvature to radius between 3" and 4".

- Roll to straighten.

- Roll to reverse initial curvature to radius between 3" and 4".

- Roll to straighten (final).

- Perform Epstein Test.

- Perform Hardness Test.

- Anneal at 1000° C

- Perform Epstein Test.

- Perform Hardness Test.

3.2 Annealing

Strips were heated in a furnace to 1000° C for more than 5 minutes. Then the door was opened about 3/4" and cooling was allowed to proceed. Scale was brushed off with a hand (nail) brush.

3.3 Hardness Testing

The Rockwell B Hardness Test was applied to the 12" samples as discussed above. 12 samples were measured (see Table 2). Average hardness was 65.88 as received, 67.06 after rolling, and 59.78 after annealing. If we characterize the stress added by the vendor as 6.1 Rockwell B units, and the addition from the test as 1.18 units, then one might describe this as the addition of 19% additional stress. We would expect to add only a few percent, at most, with currently projected fabrication techniques.

3.4 Hysteresigraph Measurements

Measurements on the Hysteresigraph were carried out at excitations up to 100 Oe. The protocol usually followed by the TSS/Materials Control Group was applied; each measurement was repeated three times and the separate measurements are reported along with the mean values. Examination of the graphed results shows hysteresis curves which cross and the reported hysteresis area is given as negative for all but the annealed data.

Property	Units	As Received	After Rolling	After Annealing
H_{max}	Oe	100.257	100.299	100.273
B_{max}	Gauss	1999	2002	1968
B_r	Gauss	469	248	265
$\mu@H_{max}$		19.940	19.957	19.626
H_c	Oe	.2553	.4539	.1091

Table 1: Hysteresigraph measurements of B-H of CarTech Temperature Compensator 30 Type 4 at nominal Room Temperature with various stress levels.

It is likely that this is due to the combination of very low hysteresis for the material and its significant temperature coefficient combined with a noticeable heating of the apparatus. Nevertheless, we report the values as given by the measurement system in Table 1. The curve plotted for the sample after annealing shows a large difference in B on the up and down ramps beginning at H values just above the knee and slowly decreasing.

We observe that the reported H_c is markedly different for the three tests. This may be real. That portion of the curve will be less affected by some of the distortions which obviously affect parts of the measurement. The changes in B_r are more likely to have been disturbed. The changes reported at high fields are certainly negligible between the as received and after rolling. The small change from the annealing may be more significant.

3.5   High Field Measurements

Using a high field technique developed at MTF[2], the B-H curve was studied for cold worked samples (Sample 8, prepare as described above) and compared with similar samples (Sample 7) from the same shipment of TC30 Type 4 material. We present the B-H curve measured in this way in Figures 1 and 2. When comparing with data (circles) with the same test configuration, we find that the data are nearly indistinguishable. Only at very low fields do we find that for the same B, there may be as much as 0.001 T difference between these materials with and without coldwork. If we compare based on the fitted data, we find that $B_r = .2375 \pm .0061(.2421 \pm .0060)$ and $\mu_h = 1.238 \pm .023(1.2295 \pm .023)$ when measured at $20.39^{\circ}C(22.74^{\circ}C)$ for the

Temperature Compensator Test - B-H Curve

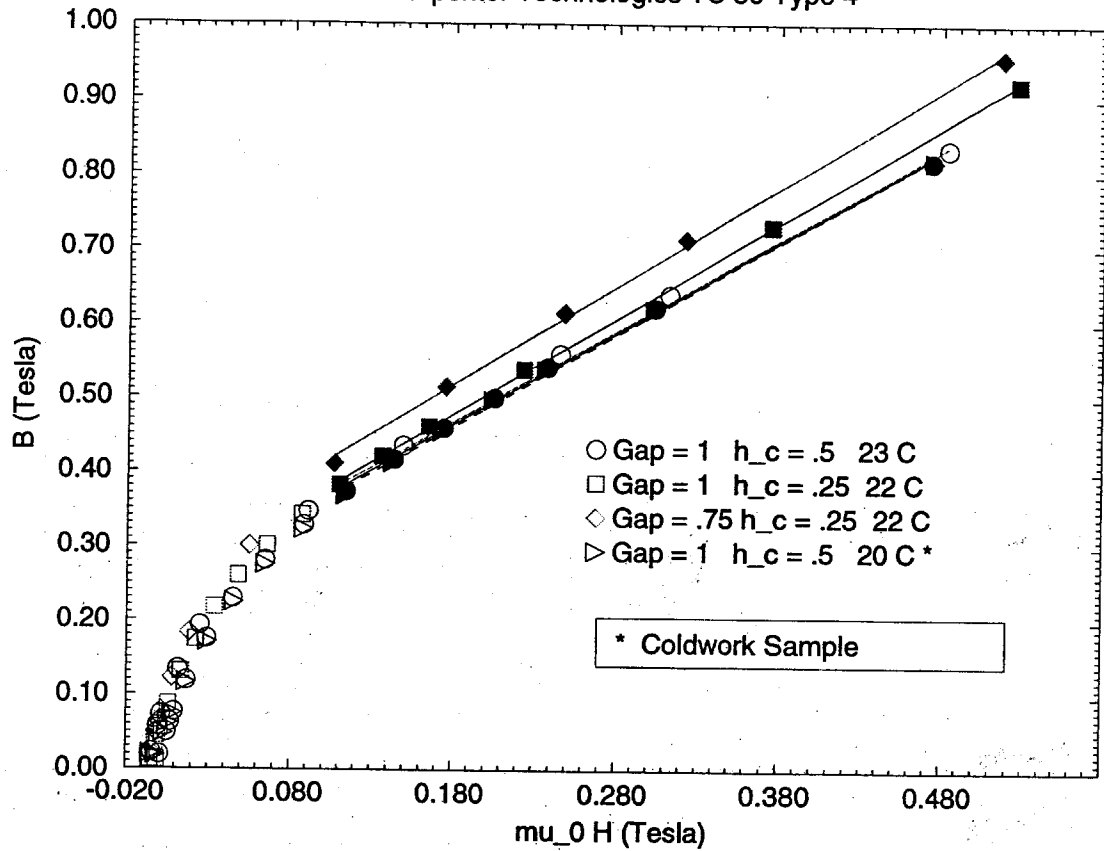### Carpenter Technologies TC 30 Type 4

Figure 1: B-H curves for Carpenter Technologies compensator materials before cold work (several configurations) and after cold work as described. Linear fits of the form $B = B_r + \mu_r \mu_0 H$ to the upramp data for $\mu_0 H$ between 0.1 and 0.5 Tesla are shown. Points used in the linear fit are plotted with filled symbols.

cold rolled (as received) sample. Correcting for the temperature difference (at 0.0050 T/k) we find cold rolled sample would have shown $B_r = .2257$ at 22.74°C. This is a 7.2% change with an error of 2.5% on each number.

We observe that the B values corresponding to values of $\mu_0 H$ of 0.001 T appear to be much lower in this test system than as reported by the Epstein Frame test used in the Hysteresigraph. We have examined our technique and

Temperature Compensator Test - B-H Curve

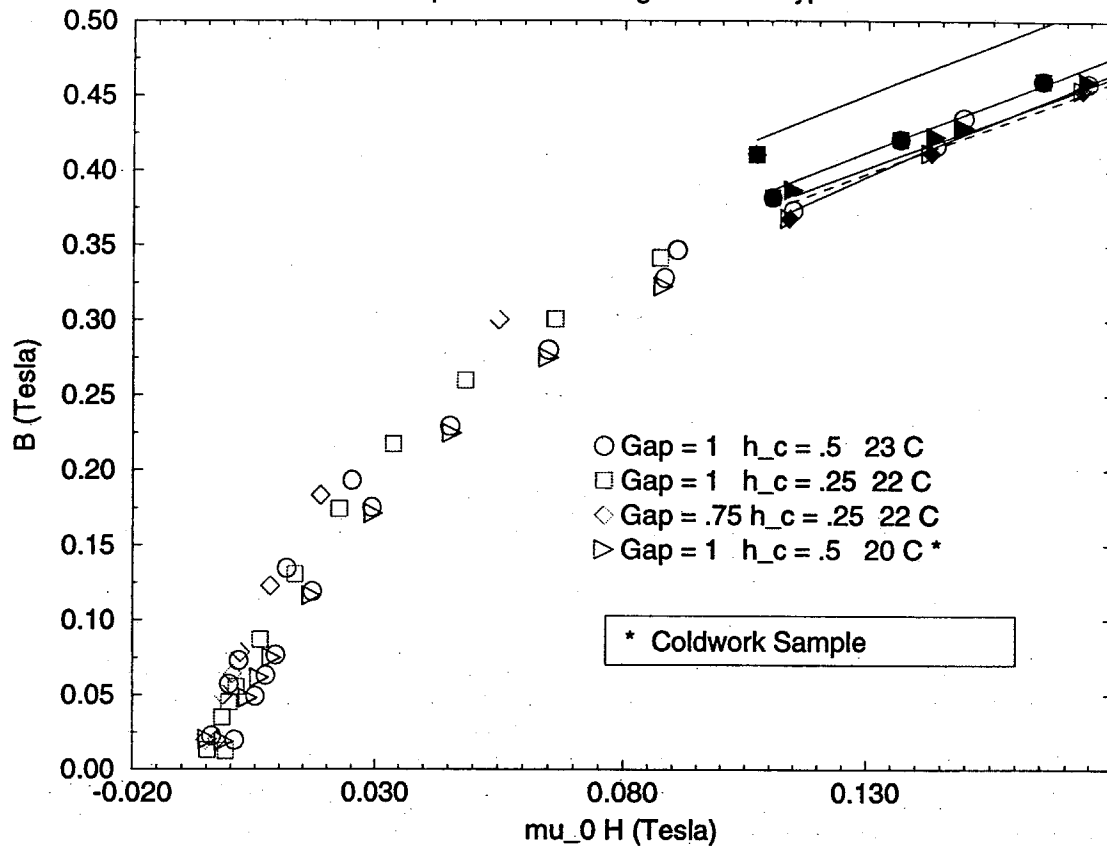## Carpenter Technologies TC 30 Type 4

Figure 2: B-H curves for Carpenter Technologies compensator materials before cold work (several configurations) and after cold work as described with scale expanded to show low field points more clearly.

find no obvious problem. We note that the results from the Epstein Frame are average values over the frame geometry and have not been corrected for geometric effects which produce non-uniform fields.

4 Conclusion

Based on room temperature measurements of the B-H curve, we conclude that substantial cold work of CarTech TC30 Type 4 material will not greatly

modify its magnetic properties. The cold work which will be involved in Fermilab magnet fabrication will be much less than was utilized for these tests. No special care should be required in handling this material in the ways now foreseen.

5   Acknowledgements

Larry Chiplis greatly assisted in both the planning for these measurements, in carrying through the sample preparation, and in collecting relevant information. Robert Riley carried out the hysteresigraph measurements. The annealing was done by Jay Hoffman. In addition to these people, I would also like to thank Darryl Orris for producing the software and assisting in hardware setup for this and other compensator measurements.

References

[1] K. Bertsche, J. F Ostiguy, and G. W. Foster. Temperature Considerations in the Design of a Permanent Magnet Storage Ring. In *Conference Record of the 1995 IEEE Particle Accelerator Conference, Dallas, May 1-5, 1995*, page to be published. Institute of Electrical and Electronic Engineers, 1995.

[2] Wufei Chen, Carl Draeger, Darryl Orris, and Bruce C. Brown. B-H Curves of some magnet Material for Temperature Compensation. Technical Report MTF-95-0017 1.1, Fermilab, September 1995.

Carpenter Temperature Compensator "30" Alloy Hardness before and after rolling. R. Riley 28/SEP/95 Hardness in Rockwell B			
Sample #	Before	After	After annealing
1	65.8	67.1	59.0
2	65.9	67.0	59.0
3	66.0	66.8	60.3
4	65.9	66.9	59.4
5	66.1	67.1	60.6
6	65.7	67.1	59.5
7	65.9	66.7	60.4
8	66.1	67.3	60.9
9	65.6	67.3	59.5
10	66.1	67.1	60.0
11	65.6	67.0	59.1
12	65.9	67.3	59.6
Average	65.88	67.06	59.78

Table #2